

Argonne National Laboratory

A STUDY OF THE INITIATION OF NUCLEATE BOILING IN THE LIQUID METALS

by

Robert E. Holtz

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NUCLEATE BOILING IN THE LIQUID METALS

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2a Refers to the saturation temperature corresponding to the pressure in the liquid

3 Refers to surface cavity opening defined in Figure 10

4 Refers to surface cavity opening defined in Figure 10

5 Refers to a fixed temperature defined in the appendix

6a Refers to the liquid pressure corresponding to a fixed temperature

7a Refers to the saturated vapor pressure corresponding to a fixed temperature

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
C	Constant in the equation for surface tension	$\text{lb}_f/(\text{in.})(^\circ\text{F})$
P	Pressure	$\text{lb}_f/\text{in.}^2$
r	Critical-bubble radius	in.
R	Radius of surface opening	in.
t	Temperature	$^\circ\text{F}$

Greek Letters

β	Defined by Equation (12)	dimensionless
σ	Surface tension	$\text{lb}_f/\text{in.}$
θ	Defined on page 9	dimensionless

Subscripts

c	Refers to critical point
g	Refers to gaseous phase
l	Refers to liquid phase
v	Refers to vapor phase
w	Refers to wall condition
ls	Refers to the saturation temperature corresponding to the pressure in the liquid
i	Refers to surface cavity opening defined in Figure 10
o	Refers to surface cavity opening defined in Figure 10
f	Refers to a fixed temperature defined in the appendix
fl	Refers to the liquid pressure corresponding to a fixed temperature
fv	Refers to the saturated vapor pressure corresponding to a fixed temperature

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ABSTRACT

An analysis has been conducted to predict the liquid superheats that will be required to initiate nucleate boiling in the alkali metals. The classical two-phase mechanical and thermal equilibrium equation is solved by applying a modeling of the behavior of the pressure in the liquid for water and the alkali metals. Curves are presented showing the liquid superheats required for nucleate boiling in sodium and potassium.

I. INTRODUCTION

Considerable information has been published on nucleate boiling. Much of this information has been for specific use in boiling-water systems. Recent interest has been focused toward the nucleate boiling characteristics of the liquid metals, especially the alkali metals and mercury. Some boiling-liquid-metal information is available; however, this information is insufficient for predicting liquid superheats required to initiate nucleate boiling in the various liquid metals.

Since a general prediction of liquid superheats required to initiate nucleate boiling is not available, the liquid superheat requirements for bubble initiation in liquid-metal systems may be analyzed by modeling empirical information gained from boiling-water studies and the liquid-metal behavior. This paper presents a modeling technique which enables the prediction of the liquid superheats required to initiate nucleate boiling in the liquid metals.

II. BACKGROUND INFORMATION

When the liquid temperature is above the saturation temperature corresponding to the pressure in the liquid, the liquid is superheated. The degree of superheat, Δt , is the difference between the superheated-liquid temperature and the saturation temperature corresponding to the pressure in the liquid. In the boiling of water, minute surface imperfections serve as

nucleation sites.^(1,2,3) It is generally accepted that a gaseous phase present in these minute cavities aids the nucleation of bubbles. A surface cavity that is a good gas trap has a good chance of becoming a nucleation site.⁽⁴⁾ The cavities that serve as nucleation sites must be microscopic in size.⁽⁵⁾

The ability of a surface cavity to entrap gases determines the effect of surface condition upon the degree of liquid superheat.⁽⁴⁾ Hence, surface condition may play a less significant role in the boiling of liquids where little or no gas phase is present. Liquid superheats required to initiate nucleate boiling in degassed water are considerably higher than those required for boiling water when more of a gas phase is present.⁽⁶⁾

Due to the precautions taken when working with boiling-alkali-metal systems and the inherent properties of these metals in the liquid state, the amount of gaseous phase present in alkali-metal heat-transfer systems will be quite small. Hence, it appears that high liquid superheats may be required to initiate nucleate boiling in the alkali metals, because the effect of surface cavities entrapping gas to form nucleation sites will be greatly reduced.

To investigate the liquid superheat requirements for initiation of nucleate boiling, consider a stable vapor bubble in thermal and mechanical equilibrium with the surrounding liquid. For thermal equilibrium to exist, the superheated liquid temperature must equal the vapor temperature inside the bubble. If the vapor contains saturated vapor or some quality, the temperature existing in the bubble represents the saturation temperature corresponding to the pressure inside the bubble. The vapor pressure within the bubble of the critical radius is higher than the pressure within the liquid by an amount expressed as follows:

$$P_v - P_\ell = 2\sigma/r. \quad (1)$$

Equation (1) assumes that noncondensibles are not present in the bubble.

Figure 1 shows the curve of saturated vapor pressure for water and the curve of liquid temperature versus pressure for boiling water. The saturated-vapor curve for water is a straight line on logarithmic paper for pressures greater than 7 psia, and may be written as

$$P_v = at_v^b, \quad (2)$$

where $a = 5.88 \times 10^{-10}$ and $b = 4.47$. The actual saturated vapor behavior was plotted from values presented by Keenan and Keyes.⁽⁷⁾ Curve "a" shows the superheated liquid temperature versus pressure in the liquid taken from UCLA⁽⁶⁾ data between 14.7 and 2500 psia. The air content contained in the

water during these experiments was approximately 0.65 ppm. This curve is also a straight line that goes through the critical point and may be expressed in the form,

$$P_{\ell} = e t_{\ell}^h, \quad (3)$$

where e and h are constants. A series of runs with degassed water at one atmosphere resulted in an average superheat requirement of 145°F for initiation of nucleate boiling.⁽⁶⁾ Curve "b" shows a straight line drawn between this data point and the critical point. This line also may be expressed in the form shown in Equation (3). The gas contained within the degassed water was slightly less than 0.01 ppm.

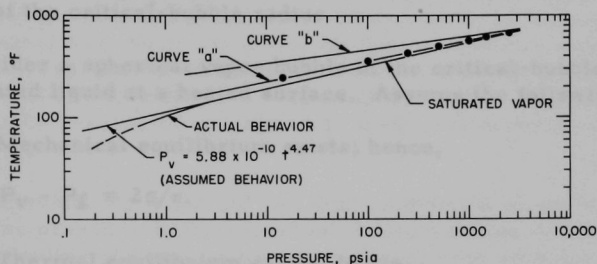


Fig. 1. Curve of Saturated Vapor Pressure for Water and Curve of Liquid Temperature versus Pressure for Boiling Water

Surface tension may be expressed in the general form,

$$\sigma = C(t_c - t_{\ell})^n.$$

For the liquid metals, the expression for the surface tension may be simplified to⁽⁸⁾

$$\sigma = C(t_c - t_{\ell}). \quad (4)$$

For water, the expression for surface tension may be written⁽⁹⁾ as

$$\sigma = 0.707 \times 10^{-6} (705.4 - t_{\ell}). \quad (5)$$

A satisfactory analytical model is not available for prediction of liquid superheats required to initiate nucleate boiling in the alkali metals. It is also unlikely that empirical correlations based entirely upon boiling-water data are suitable for liquid-metal applications. At this point, it appears reasonable to obtain as near an analytical expression as possible and then supplement empirical information so that a superheat prediction may be obtained for the liquid metals. In this light, the following model is presented.

III. THE NUCLEATE BOILING MODEL

When a bubble of the critical-bubble radius forms, the superheated liquid is pushed away from the heated surface but remains in contact with the vapor. Depending upon the surface tension and wetting characteristics of the fluid, the vapor will assume more or less a spherical shape. Since the critical-bubble radius is small compared to the thickness of the superheated layer, the critical bubble is surrounded by a nearly constant-temperature superheated liquid.

Once the critical bubble has been formed, the liquid superheat required for bubble initiation has been established. As the bubble grows, less superheat is required to sustain the bubble. For this reason, it is necessary only to examine the superheats required to sustain the smallest bubbles, that is, bubbles of the critical-bubble radius.

Consider a spherical vapor bubble of the critical-bubble radius in the superheated liquid at a heated surface. Assume the following:

- 1) Mechanical equilibrium exists; hence,

$$P_v - P_\ell = 2\sigma/r.$$

- 2) Thermal equilibrium exists; hence,

$$t_v = t_\ell = t.$$

- 3) The wall temperature is nearly equal to the vapor temperature; thus,

$$t_w = t_v = t_\ell = t. \quad (6)$$

- 4) The nucleation site on the wall has no effect upon the size of a stable vapor bubble of the critical-bubble radius in clean, degassed systems, such as in the alkali metals.

- 5) The surface tension may be expressed in the form of Equation (4).

Beyond this point in the analysis, t will be used to denote the temperature defined by assumptions (2) and (3) above.

Since the bubble of the critical-bubble radius is in thermal and mechanical equilibrium, Equation (1) may be applied. Differentiation of Equation (1) yields

$$dP_v - dP_\ell = (2/r) d\sigma - (2\sigma/r^2) dr, \quad (7)$$

and differentiation of Equation (4) yields

$$d\sigma = -Cdt. \quad (8)$$

Substitution of Equations (4) and (8) into Equation (7) yields

$$\frac{dr}{dt} = \frac{r^2}{2C(t_c - t)} \left[-\frac{dP_v}{dt} + \frac{dP_\ell}{dt} - \frac{2C}{r} \right], \quad (9)$$

where

$$r = 2C(t_c - t)/(P_v - P_\ell). \quad (10)$$

Equation (9) represents the relationship between r , t , P_v , and P_ℓ . The relationship between P_v and t may be expressed by an equation representing the saturated-vapor curve for the fluid of interest [such as Equation (2) for water]. At this point in the analysis, there are two unknown functions, dr/dt and dP_ℓ/dt , or $r = f(t)$ and $P_\ell = g(t)$. If either of these functions can be reasonably postulated or measured experimentally, Equation (9) may be solved.

To postulate $P_\ell = g(t)$ for the liquid metals, it is necessary to examine how the pressure in the superheated liquid varies with temperature for nucleate boiling of water. The expression for the behavior of the pressure in the liquid (found in the appendix) is

$$P_\ell = P_v \left(\frac{t}{t_c} \right)^\beta, \quad (11)$$

where

$$\beta = \log_\theta \left(\frac{P_{\ell f}}{P_{vf}} \right), \quad (12)$$

where θ is the base of the logarithm, and $\theta = t_f/t_c$. If the saturated-vapor-pressure curve, the critical point, and one point on the curve of superheated liquid temperature versus pressure are known, β may be evaluated and P_ℓ may be expressed by Equation (11).

A similarity modeling of the liquid-metal and water behavior is now presented. Assume that the variation of superheated liquid temperature with pressure in the liquid metals may be expressed by Equation (11), and that β is a function only of the amount of gaseous phase contained within the liquid.

Using the similarity model enables β to be calculated from data of boiling water with a known gas content, and enables β to be used in Equation (11) for liquid metals with the same amount of gaseous phase contained in the liquid. Hence, the superheats required for initiation of nucleate boiling in the alkali metals may be expressed by combining Equations (9) and (10) to obtain

$$\frac{dr}{dt} = \frac{2C(t_c - t)}{(P_v - P_\ell)^2} \left[-\frac{dP_v}{dt} + \frac{dP_\ell}{dt} - \frac{P_v - P_\ell}{t_c - t} \right], \quad (13)$$

where P_v is expressed by an empirical correlation of the saturated-vapor-pressure curve for the fluid of interest, and P_ℓ is expressed by Equation (11), with β evaluated from Equation (12) by using boiling-water data.

At the critical point (P_c, t_c), there is no separation into two phases; that is, there is no transition from one phase to another. The critical-bubble radius at the critical point must equal zero because boiling, as defined by a transition from the liquid to vapor phase, does not take place. Thus, the boundary condition for Equation (13) may be expressed at $t = t_c, r = 0$.

The degree of liquid superheat may also be solved directly by using Equations (2) and (11) to obtain a value of P_v for a given value of t . Applying either the expression for the saturation curve or graphical techniques enables the saturation temperature corresponding to P_v to be found; hence, $(t - t_{\ell s})$ may be found. The function $r = f(t)$ may also be found directly by using Equations (1), (2), and (11).

In this analysis, the former method was applied with the aid of an analog computer.

IV. APPLICATION OF THE NUCLEATE BOILING MODEL

Before the nucleate boiling model is applied to sodium and potassium, the nucleate boiling model is used to predict critical-bubble radii and liquid superheats required for boiling degassed water with $\beta = 3.38$. This value of β , corresponding to curve "b" in Figure 2, makes possible the calculation of the pressure existing within the superheated liquid with a gas content of approximately 0.01 ppm. The critical-bubble radius, plotted against the saturated temperature corresponding to the pressure in the liquid, is shown in Figure 2. Note that the critical-bubble radius decreases as $t_{\ell s}$ increases. At one atmosphere pressure ($t_{\ell s} = 212^\circ\text{F}$), the critical-bubble radius is 3.7×10^{-6} in.

where σ is 37 dyn/cm and ρ is 958 kg/m³. Equation (14) may also be written,

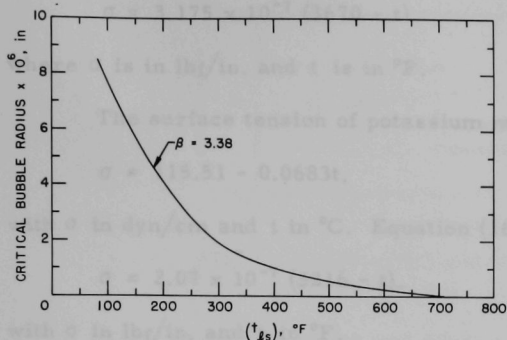


Fig. 2

Critical-bubble Radius
versus t_{ls} for Initiation
of Nucleate Boiling in
Water

Figure 3 shows the degree of liquid superheat required to initiate nucleate boiling in degassed water ($\beta = 3.38$). The degree of liquid superheat has a maximum value of 147°F at $t_{ls} = 185^\circ\text{F}$. Beyond this point, the degree of liquid superheat decreases as t_{ls} increases. The liquid superheats shown in curve "b" in Figure 1 necessarily correspond with those predicted by the nucleate boiling model.

Fig. 3

Degree of Liquid Superheat
versus t_{ls} for Initiation of
Nucleate Boiling Water

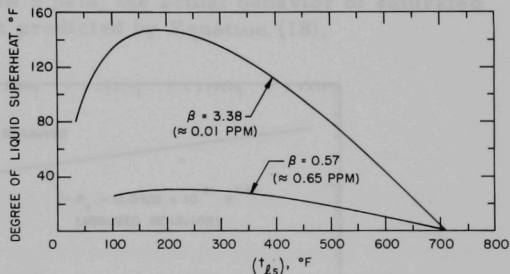


Figure 3 also shows the degree of liquid superheat required to initiate nucleate boiling in water with a gas content of approximately 0.65 ppm ($\beta = 0.57$). This curve corresponds to the liquid superheats shown in curve "a" of Figure 1.

Before the nucleate boiling model can be used for predicting the liquid superheats required to initiate nucleate boiling in sodium and potassium, sufficient thermophysical property information must be available.

The surface tension of sodium may be expressed⁽¹⁰⁾ as

$$\sigma = 202 - 0.10t, \quad (14)$$

where σ is in dyn/cm and t is in $^\circ\text{C}$. Equation (14) may also be written,

$$\sigma = 3.175 \times 10^{-7} (3670 - t) \quad (15)$$

where σ is in $\text{lb}_f/\text{in.}$ and t is in $^{\circ}\text{F}$.

The surface tension of potassium may be written⁽¹¹⁾ as

$$\sigma = 115.51 - 0.0683t, \quad (16)$$

with σ in dyn/cm and t in $^{\circ}\text{C}$. Equation (16) may also be written as

$$\sigma = 2.07 \times 10^{-7} (3216 - t), \quad (17)$$

with σ in $\text{lb}_f/\text{in.}$ and t in $^{\circ}\text{F}$.

The variation of saturated sodium vapor pressure with temperature (from Ref. 10) is plotted in Figure 4. For saturated vapor pressures beyond 5 psia, the relationship between saturated vapor pressure and temperature may be expressed as

$$P_v = 0.0925 \times 10^{-21} t^{7.23}. \quad (18)$$

It is seen that at pressures below 5 psia, the actual behavior of saturated sodium vapor deviates from that predicted by Equation (18).

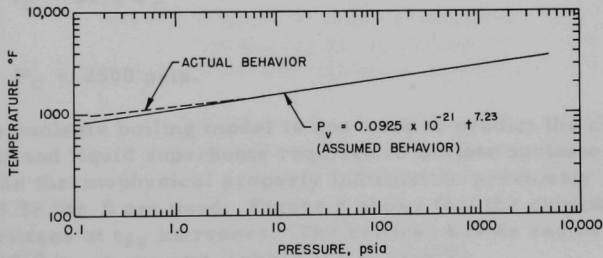


Fig. 4. Curve of Saturated Vapor Pressure for Sodium

The variation of saturated potassium vapor pressure with temperature from Ref. 12 is plotted in Figure 5. Beyond 10 psia, the saturated vapor pressure of potassium may be expressed as

$$P_v = 0.0833 \times 10^{-18} t^{6.44}. \quad (19)$$

At pressures below 10 psia, the actual behavior of potassium vapor deviates from that predicted by Equation (19).

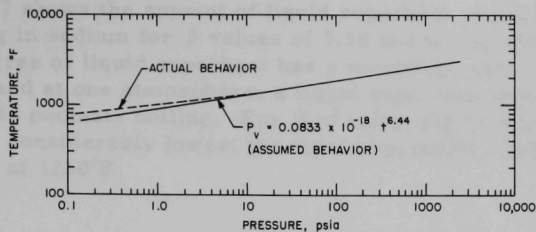


Fig. 5. Curve of Saturated Vapor Pressure for Potassium

The critical pressures and temperatures used in this analysis are as follows:

- 1) For sodium,⁽¹⁰⁾

$$t_c = 3631^\circ\text{F},$$

and

$$P_c = 5042 \text{ psia}.$$

- 2) For potassium,⁽¹²⁾

$$t_c = 3095^\circ\text{F},$$

and

$$P_c = 2500 \text{ psia}.$$

The nucleate boiling model is now used to predict the critical-bubble radii and liquid superheats required to initiate nucleate boiling in sodium. The thermophysical property information previously shown and a value of 3.38 for β are used. Figure 6 shows that the critical-bubble radius decreases as $t_{\ell s}$ increases. The critical-bubble radius has a value of 12.25×10^{-6} in. at one atmosphere ($t_{\ell s} = 16.8^\circ\text{F}$).

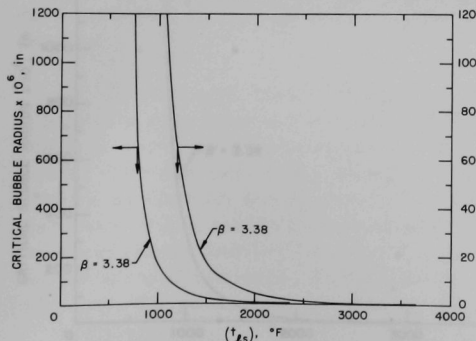


Fig. 6

Critical-bubble Radius versus $t_{\ell s}$ for Initiation of Nucleate Boiling of Sodium

Figure 7 shows the amount of liquid superheat required to initiate nucleate boiling in sodium for β values of 3.38 and unity. Using β equal to 3.38, the degree of liquid superheat has a maximum value of 510°F at $t_{\ell s}$ of 1100°F; and at one atmosphere, a liquid superheat of 474°F is required to initiate nucleate boiling. For β of unity, the predicted liquid superheats are considerably lower; the maximum liquid superheat of 173°F occurs at a $t_{\ell s}$ of 1250°F.

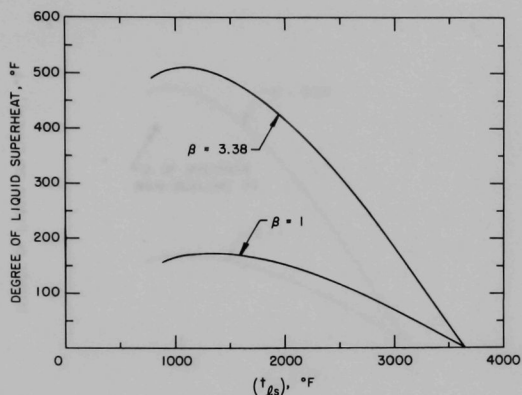


Fig. 7. Degree of Liquid Superheat versus $t_{\ell s}$ for Initiation of Nucleate Boiling of Sodium

Using the nucleate boiling model, β equal to 3.38, and Equations (17) and (19), the critical-bubble radii and liquid superheats required to initiate nucleate boiling in potassium are found. Figure 8 shows that the critical-bubble radius decreases as $t_{\ell s}$ increases. The critical-bubble radius has a value of 7.40×10^{-6} in. at one atmosphere ($t_{\ell s} = 1400^\circ\text{F}$).

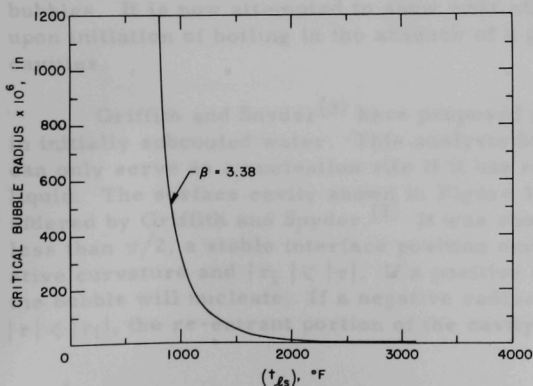


Fig. 8
Critical-bubble Radius versus $t_{\ell s}$ for Initiation of Nucleate Boiling of Potassium

Figure 9 shows the degree of liquid superheat required to initiate nucleate boiling in potassium for β values of 3.38 and unity. For β equal to 3.38, the degree of liquid superheat has a maximum value of 474°F at a $t_{\ell s}$ of 900°F, and at one atmosphere, a liquid superheat of 435°F is required to initiate nucleate boiling. For a β value of unity, the predicted liquid superheats are considerably lower; the maximum liquid superheat of 165°F occurs at a $t_{\ell s}$ of 1000°F.

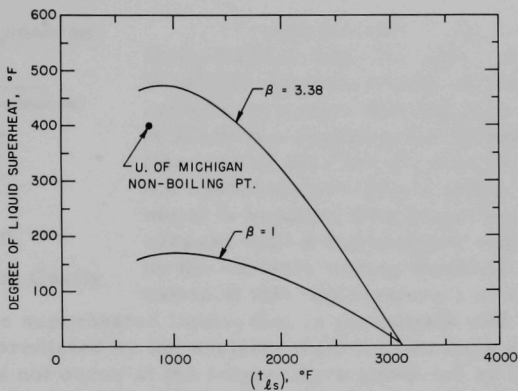


Fig. 9. Degree of Liquid Superheat versus $t_{\ell s}$ for Initiation of Nucleate Boiling of Potassium

V. THE EFFECT OF SURFACE CONDITION

It is generally accepted that the surface condition has a definite effect upon bubble nucleation in boiling water. Also, it has been shown that the presence of a gaseous phase within the liquid aids the nucleation of bubbles. It is now attempted to show what effect the surface condition has upon initiation of boiling in the absence of a gaseous phase within the surface cavities.

Griffith and Snyder⁽³⁾ have proposed a mechanism of void formation in initially subcooled water. This analysis has shown that a surface cavity can only serve as a nucleation site if it has not, at any time, been filled with liquid. The surface cavity shown in Figure 10 is similar to the cavity considered by Griffith and Snyder.⁽³⁾ It was shown that for an angle of contact less than $\pi/2$, a stable interface position exists within the cavity for a negative curvature and $|r_i| < |r|$. If a positive curvature exists and $|r| < |r_0|$, the bubble will nucleate. If a negative radius of curvature exists and $|r| < |r_i|$, the re-entrant portion of the cavity will fill with liquid and

deactivate the cavity. Hence, a cavity may serve as a nucleation site only when $|r_0| > |r|$, and for when the curvature is negative, $|r_1| < |r|$. The values of r used in the analysis are calculated from the equation

$$P_v + P_g - P_l = 2\sigma/r. \quad (20)$$

When the gaseous phase contained within the surface cavity is an insignificant amount ($P_g \approx 0$), Equation (20) becomes identical to Equation (1).

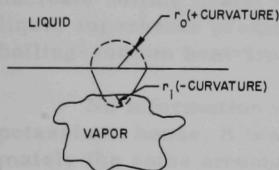


Fig. 10

Typical Surface Cavity

contact with the superheated liquid, that is compatible with the critical-bubble radius predicted by the nucleate model, nucleation will occur. If nucleation does not occur at the temperature predicted by the nucleate boiling model, the degree of liquid superheat will increase until a surface cavity exists that is compatible with the excessive liquid superheat; at this point, a bubble will form. Hence, the use of the critical-bubble radius serves as a tool for predicting the minimum liquid superheats required to initiate bubble nucleation.

The surface cavities that serve as nucleation sites are microscopic in size;⁽⁵⁾ thus, a large variety of cavity sizes is likely to exist on a surface. Hence, the amount of excessive liquid superheat beyond that predicted by the nucleate boiling should be relatively small.

VI. DISCUSSION OF RESULTS

The results of the nucleate boiling model indicate that high liquid superheats may be required to initiate nucleate boiling in both sodium and potassium. These high liquid superheats are in fair agreement with the analytical results of Krakoviak⁽¹³⁾ and the experimental evidence obtained by the University of Michigan.⁽¹⁴⁾

It has been shown that the amount of gaseous phase contained within the liquid has a significant effect upon the degree of liquid superheat required to initiate nucleate boiling. The inherent properties of most of the alkali metals are such that a gaseous phase, other than noble gases, will form

To demonstrate further the effect of surface condition upon the liquid superheats required to initiate nucleate boiling of the liquid metals, consider a system that has been evacuated prior to fill with a degassed liquid metal. Surface cavities may or may not fill with liquid depending upon the conditions previously shown. As the liquid metal is supplied with heat, the temperature increases until a temperature equal to that predicted by the nucleate boiling model is obtained. If there exists at this temperature a surface cavity, in

compounds etc. with the alkali metals. For example, sodium is inert to only the noble gases helium, argon, neon, krypton, and xenon.⁽¹⁵⁾ The solubility of argon gas in sodium is of the order of 0.01 ppm.⁽¹⁶⁾

Consider the situation in which sodium containing an insignificant amount of a gaseous phase is put into a clean, evacuated system and pressurized with an argon gas blanket. The sodium should contain approximately 0.01 ppm of an argon gaseous phase only. The β value of 3.38 used in the nucleate boiling model was based upon a 0.01-ppm gas content; hence, the liquid superheats predicted by the model should be useful in the design of boiling-sodium heat-transfer systems.

No information was found as to the solubility of argon gas in liquid potassium; hence, it may be assumed that potassium will contain approximately the same amount of gaseous phase as does sodium. Figure 9 shows the 400°F liquid superheat obtained by the University of Michigan⁽¹⁴⁾ in which nucleate boiling of potassium did not occur. It is seen that this liquid superheat is less than that predicted by the nucleate boiling model for initiation of nucleate boiling in liquid potassium.

By comparison with water, Krakoviak⁽¹³⁾ has calculated the liquid superheat required to initiate a vapor bubble from a surface immersed in a liquid metal. Comparing potassium and sodium with water where a 30°F liquid superheat is required to initiate nucleate boiling at one-atmosphere pressure, it was calculated that 125 and 258°F liquid superheats are required to initiate nucleate boiling in potassium and sodium, respectively. Comparing liquid-metal systems with distilled, degassed water at one atmosphere, boiling from a clean surface, it was calculated that liquid superheats of 375 and 774°F are required to initiate nucleate boiling in potassium and sodium, respectively. The results of Krakoviak⁽¹³⁾ for initiation of nucleate boiling of sodium in a clean system at one atmosphere are considerably higher than the degree of liquid superheat predicted by the modeling technique presented in this report. However, the result of Krakoviak for initiation of nucleate boiling of potassium in a clean system at one atmosphere is only slightly below the results predicted by the modeling technique.

The β value of 3.38 is used because it appears to be the best available information that may be applied to boiling-liquid-sodium systems that are pressurized by means of an argon gas blanket. In actual boiling-alkali-metal systems, β values may differ from the values used in this analysis. For example, in systems where an inert cover gas other than argon is utilized, the solubility of that gas in the liquid alkali metal may be quite different from the solubility of argon gas in liquid sodium. Hence, liquid superheats required to initiate nucleate boiling in a liquid-metal system may be considerably different from those predicted by using a β value of 3.38.

The analysis is based upon the five assumptions previously shown (pages 10 and 11). When assumptions (1) and (2) are used, the liquid superheat required to sustain a spherical volume of vapor in thermal and mechanical equilibrium is obtained. These assumptions may be a somewhat idealized case of the actual boiling phenomenon.

The superheated layer thickness for boiling water is of the order of 10^{-3} in.,⁽¹⁷⁾ while the bubble radii for water discussed in this report are approximately two orders of magnitude smaller. Thus, the wall temperature, vapor temperature, and liquid temperature at the wall appear to be nearly the same, and assumption (3) appears justified. Due to the high thermal conductivity of the alkali metals, the thermal boundary layer for the alkali metals should be considerably higher than that in boiling water.

According to assumption (4), the nucleation site on the wall has no effect upon the size of a stable vapor bubble of the critical-bubble radius. It has been shown that the surface condition has a significant effect upon the degree of liquid superheat in the boiling of water because surface cavities entrap gases, thus lowering the liquid superheat required for boiling. In the boiling of degassed water and the alkali metals, little or no gas phase will be present in the system; thus, the effect of the surface entrapping gas and lowering the required liquid superheat should be far less significant. The effect of the surface condition for this case was discussed in Section V.

The applied equations for surface tension are widely used; hence, assumption (5) appears valid.

The expressions used for thermophysical properties in these calculations closely match the property data presented in Refs. 10, 11, 14, and 15 over the range presented. The use of Equations (18) and (19) for expressing the saturation curve is within 1% of the data presented by Dunning⁽¹⁰⁾ and Weatherford *et al.*⁽¹²⁾ for sodium and potassium, respectively. As the thermophysical properties become more precisely known, more rigorous expressions may be utilized with this modeling technique.

This analysis does not present a new boiling theory, but does enable solving the equilibrium bubble equation [Equation (1)] for the alkali metals by utilizing a modeling of the alkali-metal and degassed-water behavior to find $P_\ell = g(t)$. The results obtained appear in fair agreement with the results of other investigators.^(12,13) Hence, this approach may be used as a tool for examining and comparing future experimental liquid superheat measurements for boiling liquid metals.

APPENDIX

Behavior of Pressure in the Liquid

To postulate $P_\ell = g(t)$ for the liquid metals, it is necessary to examine how the pressure in liquid varies with temperature for nucleate boiling of water. As shown in Figure 1, the liquid pressure during nucleate boiling of water may be expressed in the form of Equation (3),

$$P_\ell = et^h,$$

where e and h are constants depending upon the amount of gaseous phase present in the liquid.

It has also been shown that the saturated-vapor curve for water may be expressed by Equation (2),

$$P_v = at^b,$$

where $a = 5.88 \times 10^{-10}$ and $b = 4.47$ for boiling water.

Inspection of boiling-water data shows that both Equations (2) and (3) pass through the critical point ($t_c = 705.4^\circ\text{F}$, $P_c = 3206.2$ psia). Now, if one point other than the critical point is known on the $P_\ell = g(t)$ curve for water with a known gas content, the relationship, $P_\ell = g(t)$ may be found.

In solving for $P_\ell = g(t)$, the following conditions are used:

- (1) At $t = t_c$, $P_\ell = P_v = P_c$.
- (2) At $t = t_f$, $P_\ell = P_{f\ell}$ and $P_v = P_{fv}$.

The constants a , b , e , and h are found to be

$$a = \frac{P_c}{t_c [\log_\theta (P_{fv}/P_c)]}, \quad (21)$$

$$b = \log_\theta (P_{fv}/P_c), \quad (22)$$

$$e = \frac{P_c}{t_c [\log_\theta (P_{f\ell}/P_c)]}, \quad (23)$$

and

$$h = \log_{\theta}(P_v/P_c), \quad (24)$$

where θ is the base of the logarithm, and $\theta = t_f/t_c$.

Thus,

$$P_v = \left[\frac{P_c}{t_c [\log_{\theta}(P_{fv}/P_c)]} \right] t^{\log_{\theta}(P_{fv}/P_c)}, \quad (25)$$

and

$$P_{\ell} = \left[\frac{P_c}{t_c [\log_{\theta}(P_f/P_c)]} \right] t^{\log_{\theta}(P_f/P_c)}. \quad (26)$$

Combining Equations (25) and (26) results in the following expression:

$$P_{\ell} = P_v(t/t_c) \log_{\theta}(P_{fv}/P_{f\ell}). \quad (27)$$

Equation (27) may be expressed as

$$P_{\ell} = P_v(t/t_c)^{\beta}, \quad (28)$$

where

$$\beta = \log_{\theta}(P_{fv}/P_{f\ell}) \quad (29)$$

It is seen that β is dependent upon the critical temperature, any point on the saturated-vapor curve, and a corresponding point on the curve for temperature versus liquid pressure. The point on the curve for temperature versus liquid pressure is highly dependent upon the gaseous phase contained within the superheated liquid as shown in Figure 1.

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REFERENCES

1. S. G. Bankoff, The Prediction of Surface Temperature at Incipient Boiling, Second National Heat Transfer Conference, AIChE-ASME (1958).
2. P. Griffith and J. D. Wallis, The Role of Surface Condition in Nucleate Boiling, Chemical Engineering Symposium Series 56, No. 30, pp. 49-63 (1960).
3. P. Griffith and G. Snyder, The Mechanism of Void Formation in Initially Subcooled Systems, MIT-9041-26 (Sept 1963).
4. S. G. Bankoff, Entrapment of Gas in the Spreading of Liquid Over a Rough Surface, Amer. Inst. Chem. Engr. J. 4, pp. 24-26 (1958).
5. J. W. Westwater, Things We Don't Know About Boiling Heat Transfer, Research in Heat Transfer, Pergamon Press (1963).
6. H. Buchberg, et al., Studies in Boiling Heat Transfer, University of California, COO-24 (Mar 1951).
7. J. H. Keenan and F. G. Keyes, Thermodynamic Properties of Steam, John Wiley and Sons, N. Y. (1936).
8. A. V. Grosse, The Relationship Between the Surface Tension and Energies of Liquid Metals and Their Critical Temperatures, J. Inorg. Nucl. Chem. 24, pp. 147-156, (1962).
9. R. J. Weatherhead, Nucleate Boiling Characteristics and the Critical Heat Flux Occurrence in Subcooled Axial-flow Water Systems, ANL-6675 (Mar 1963).
10. E. L. Dunning, The Thermodynamic and Transport Properties of Sodium and Sodium Vapor, ANL-6246 (Oct 1960).
11. J. W. Cooke, Thermodynamic Property Measurements of Alkali Liquid Metals, Third Annual Conf. on High Temperature Liquid-Metal-Heat-Transfer Technology at O.R.N.L. (Sept 1963).
12. W. E. Weatherford, Jr., J. C. Tyler, and P. M. Ku, Properties of Inorganic Energy Conversion and Heat Transfer Fluids for Space Applications, WADD Tech. Report 61-96, (Nov 1961).
13. A. I. Krakoviak, Notes on the Liquid-Metal Boiling Phenomena, ORNL-TM-618 (July 10, 1963).

14. R. E. Balzhieser, Investigation of Boiling Liquid Metal Heat Transfer, University of Michigan, RTD-TDR-63-4130 (Nov 1963).
15. Liquid Metal Handbook, Sodium-NaK Supplement, USAEC and Department of The Navy (July 1, 1955).
16. Irving Johnson, ANL, Chemical Engineering Division, personal communication.
17. Y. Y. Hsu, On the Size Range of Active Nucleation Cavities on a Heated Surface, ASME Jour. of Heat Transfer, 84C (Aug 1962).

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